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U.S. EPA REGIONAL OXIDANT MODEL - BACKGROUND AND OVERVIEW

by

K. L. Schere
Environmental Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

N. C. Possiel
On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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16. ABSTRACT

Experience with analyzing ambient air quality data for photochemical pollutants from the Northeast U.S. has shown that interurban and regional transport can have a major effect on ozone concentrations over large areas of that section of the country. EPA's Regional Oxidant Model was designed to simulate the physical and chemical processes that are responsible for photochemical smog within the earth's boundary layer on a 1000 km horizontal scale. The framework for the model includes 3 prognostic layers in the vertical extending through to the top levels of cumulus cloud convection and a shallow diagnostic surface layer designed to account for the subgrid scale chemical effects of a heterogeneous emissions distribution. Among the processes the model accounts for are advective transport, photochemistry, nighttime wind shear and turbulence episodes, cumulus cloud effects on vertical mass transport and photochemical reaction rates, terrain influences, biogenic and anthropogenic emissions, and removal by deposition. The initial data base for regional model application is that collected during the NECRMP field studies of 1979-80 in the Northeast U.S. For this application the model domain has 60 grid cells E-W and 42 cells N-S with a grid spacing of approximately 18.5 km. Several multi-day periods from the data base will be chosen for model evaluation.

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Introduction

The development of a photochemical model capable of simulating regional transport of ozone and its precursors is the focus of an extensive program now in progress at the U.S. Environmental Protection Agency (EPA). This model, the Regional Oxidant Model (ROM) is designed for use in evaluating the effectiveness of various control strategies needed to provide for attainment of the ozone NAAQS. The model will be evaluated for the Northeast U.S. where various studies have demonstrated the occurrence of widespread episodes of high ozone concentrations [1,2]. The purposes of this paper are to highlight the types of issues that could be addressed using the Regional Oxidant Model and to describe the structure of this model.

Regional Oxidant Issues

Several investigations have revealed that relatively high concentrations of ozone (90-100 ppb) are transported aloft overnight from areas of the Midwest across portions of the Northeast [3,4]. Ozone concentrations of this magnitude become important on the second and third days of transport. At that time, transported ozone coupled with aged photochemical by-products can contribute to high rural ozone concentrations or to urban plume chemistry. In addition to multi-day transport, high concentrations, on the order of 150 ppb, are often measured at surface sites more than a hundred kilometers downwind of several northeastern cities. An example of this situation is shown in Figure 1. In this case the spatial extent of urban ozone plumes generated from emissions in the major cities is clearly evident from the ozone isopleths.

Of major concern for strategy planning, development, and implementation is that urban areas encompass portions of several States (e.g., the New York City metropolitan area includes parts of New Jersey, New York, and Connecticut). Also, interurban transport can result in violations of the ozone NAAQS in far downwind States which do not include portions of the contributing urban area. For example, portions of the New York City plume, containing ozone concentrations on the order of 200 ppb have been observed on occasion across parts of Rhode Island and Massachusetts [5]. The complexity of interurban transport may be exacerbated by the close proximity of cities, such as Washington, DC and Baltimore, MD where the concentration of pollutant transport can be influenced by the chemical interaction of two or more urban plumes.

The application of urban scale models is the cornerstone of EPA's regulatory program to determine the reductions of volatile organic compound (VOC) emissions needed to achieve attainment of the ozone NAAQS. However, it is recognized that such models are not designed for the complex spatial and temporal scales of the ozone problem described above. Therefore, the major utility of the regional model lies in its ability to simulate interurban and regional transport scenarios for single and multi-day high ozone events.

Possible applications of the ROM include its use for estimating base case and future year (post-control) boundary conditions in urban scale model applications for those northeastern cities which may have difficulty attaining the ozone NAAQS by 1987. In addition, there is considerable interest in assessing the impact of urban VOC reductions on ozone concentrations in far downwind rural areas. At issue is that, although the implementation of control strategies will reduce the magnitude of peak ozone within the urban plume, the location of the peak may shift further downwind and could actually increase ozone levels in more remote rural areas. One concern is that this would increase the potential damage to several crop species and other vegetation from elevated ozone concentrations. Also, a decrease in urban ozone production, due to lower VOC emissions, may result in higher NO_x concentrations available for long-range transport to downwind rural or urban areas. It is possible that this might heighten the ozone production potential of anthropogenic VOC emissions outside urban areas, and perhaps naturally emitted hydrocarbons. This would increase the contribution of such sources to the regional ozone burden. The capabilities of the ROM as a tool for use in addressing these types of issues result from the structure of its design as described in the following section.

Regional Oxidant Model - Structure and Organization

The ROM has been designed in a general fashion in order to simulate the important chemical and physical processes responsible for the production of photochemically produced ozone on scales of 1000 km, or several days of transport time. These processes include horizontal transport, atmospheric chemistry, nighttime wind shear and turbulence episodes associated with the nocturnal jet, cumulus cloud effects on vertical mass transport and photochemical reaction rates, mesoscale vertical motions induced by terrain and the large scale flow, terrain effects on advection, diffusion and deposition, sub-grid scale chemistry processes, emissions of natural and anthropogenic precursors, and wet and dry removal processes. They are mathematically simulated in a 3-D Eulerian framework in a model with 3 1/2 vertical layers extending through the boundary layer and the capping inversion or cloud layer. Horizontal resolution varies slightly over the model domain because the ROM domain is defined in terms of curvilinear coordinates. At present, horizontal resolution is approximately 20 km.

Detailed descriptions of the theoretical basis and design of the ROM are available elsewhere [6,7]. This section presents a brief summary of some of the unique features of the model. Figures 2 and 3 display the vertical structure during daytime and nighttime conditions, respectively. The top 3 layers are prognostic (predictive) and are free to locally expand and contract in response to changes in the physical processes occurring therein. The bottom layer is a shallow diagnostic surface layer designed to approximate the sub-grid scale effects on chemical reaction rates from a spatially heterogeneous emissions distribution.

During the day, the top model layer represents the synoptic-scale subsidence inversion, the base of which is typically 1-2 km above the ground. A downward flux of stratospheric ozone, specified as a boundary condition, may be considered in this layer. Also, if cumulus clouds are present, an upward flux of ozone and precursor species is injected into the layer by penetrative convection. At night, ozone and the remnants of other photochemical reaction products may remain in this layer and be transported long distances downwind. Layers 1 and 2, above the surface layer, model the depth of the well-mixed layer during the day. In local areas where strong winds exist or the surface heat flux is weak there can exist substantial wind shear in the lowest few hundred meters above ground. This phenomenon can be treated separately in layer 1. Also, over large lakes or near seacoasts there often exists a thermal internal boundary layer that can be modeled in layer 1. Deposition on terrain features that protrude above the surface layer are also handled here. At night layer 2 represents the remains of the daytime mixed layer. As stable layers form near the ground and suppress turbulent vertical mixing a nocturnal jet forms above the stable surface layer and can transport aged pollutant products and reactants considerable distances. This flow in layer 1 is modeled explicitly and is described further below. Periodically the jet breaks down and allows sporadic episodes of vertical mixing at night between layer 1 and the surface layer, which is a reservoir of nighttime emissions from low level sources. At night, emissions from tall stacks and warm cities are injected directly into layers aloft. During an entire simulation period horizontal advection and diffusion and gas phase chemistry are modeled prognostically in the upper 3 layers.

The surface layer, model layer 0, parameterizes processes occurring within the lowest 100 m above ground. They include the sub-grid scale effects on chemical reaction rates from the spatially heterogeneous species concentrations resulting from point and line source emissions injections, the stagnation of surface emissions in stable surface layers, and the deposition of pollutants on vegetation and other surfaces. The variability of pollutant species concentrations within the ROM grid cells can have a significant effect on second-order chemical processes, such as occur in photochemical smog reactions. In averaging species concentrations over the volume of one grid cell information is lost concerning the fine scale structure. This may potentially cause erroneous reaction rates for NO, NO_2, and O_3 to be calculated. This problem can be made less severe by minimizing the averaging interval for rate calculations or parameterizing the fine structure effects. The latter approach is taken in the ROM.

In essence, layer 0 is simply a sophisticated lower boundary condition on layer 1. It is designed to estimate species concentrations in a diagnostic manner using current concentrations from layer 1 immediately above, along with local values of independent parameters such as emissions rates and deposition velocities. An advantage of this design is that no additional computer storage is required beyond that needed for the other 3 model layers. Implicit in the design of layer 0 parameterization is the assumption that horizontal transport within the layer is negligibly small and that the effects from phenomena occurring here are transferred to the rest of the model domain only through vertical mass fluxes. One of the

practical benefits of the parameterization scheme is that it provides an estimate of the magnitude of spatial variations in layer 0 concentrations. This will be especially useful in comparing predicted cell-averaged concentrations with values observed at fixed point monitoring sites. The actual evaluation of concentration and expected range of variation is not performed at every time step and in every grid cell, but rather only at those times and sites where ground-level concentration estimates are needed.

Outside of the plumes from emission line sources in layer 0, pollutant species are considered somewhat aged and thus, the ratios of their concentrations are probably close enough to their chemical equilibrium values that little reaction occurs during the time that species are resident in that layer. Thus, all pollutants except NO, NO_2, and O_3 are treated as pseudo-inert substances in that the time scales of their reactions are much larger than the characteristic residence time of material within layer 0. Within reactive emissions line source plumes chemical reactions should proceed rapidly because concentrations of NO_x are greatly disturbed from their chemical equilibrium values by fresh emissions. It is assumed that only the species NO, NO_2, and O_3 undergo significant chemical conversion within these plumes, and thus are the only species to be affected by sub-grid scale concentration variations within layer 0. The rate of reaction among these species is considered to be infinite here. The expected range of sub-grid scale concentrations is a function of the fraction of the layer 0 grid cell occupied by source emissions plumes and the concentrations of the particular species both inside and outside of such plumes.

As mentioned above, the effects from processes occurring in layer 0 propagate into the prognostic portion of the model domain through upward vertical fluxes into layer 1. When cumulus clouds are present in a layer 3 cell above a cell in the surface layer the vertical mass flux is partially diverted from injection into layer 1 to injection into the cumulus cloud of layer 3. In the atmosphere strong thermal vertical updrafts, primarily originating near the surface in the lowest portion of the mixed layer, feed young growing cumulus clouds with vertical air currents that extend from the ground to well above the top of the mixed layer in one steady upward motion. The dynamic effects of this transport process and daytime cloud evolution may have significant effects on the chemical fate of pollutants caught up in the process. For example, fresh emissions from the surface layer may be injected into a warm thermal and rise, essentially unperturbed, to the top of the mixing layer where they enter the base of a growing cumulus cloud. Within the cloud the chemical processes of ambient pollutant species are suddenly altered by the presence of liquid water and the attendant attenuation of sunlight. The presence of young cumulus clouds implies that the atmosphere above the earth's boundary layer is too stably stratified for thermals to penetrate higher. When this happens the air composing the tops of these clouds dives back into the mixed layer and is heated by compression on its descent. Eventually the liquid water droplets evaporate leaving behind the residue of the aqueous phase reactions. Ultimately, the parcel arrives again at the

surface level where new emissions may be injected into it and ground deposition may occur, and the process may begin again. The time required for one complete cycle would typically be 30-50 min with perhaps one-tenth of the time spent in the cloud stage.

Within the ROM system, a sophisticated sub-model simulates this cloud flux process and its impact on the material fluxes among all the model's layers. In the current implementation of the chemical kinetics, liquid phase chemistry is not modeled and thus part of the effects from the cloud flux processes are not seen in the simulations. Future versions of the chemical kinetics may include liquid phase reactions. The magnitude of the mass flux proceeding directly from the surface layer to the cloud layer is modeled as proportional to the observed amount of cumulus cloud coverage and inversely proportional to the observed depth of the clouds.

Horizontal transport within the top 3 layers is governed by hourly wind fields interpolated from periodic wind observations made from upper air soundings and surface measurements. One exception occurs during the nighttime simulation period for layer 1. At this time the lowest few hundred meters of the atmosphere above the ground may become stable as a radiation inversion forms near the ground. This entire layer is "decoupled" from the rest of the old daytime mixed layer. Wind speeds increase in this inversion layer and the nocturnal jet forms, capable of carrying ozone, other reaction products, and emissions from tall stacks and warm cities considerable distances downwind. This phenomenon is potentially quite significant in modeling regional scale air quality. Because standard weather observations of winds do not have the spatial or temporal resolution necessary to diagnostically determine this flow over large distances with any confidence, a sub-model within the ROM system was developed to simulate the nocturnal flow regime in layer 1 only.

The prognostic flow sub-model is activated only when a surface inversion is present over most of the model domain. At all other times the flow in layer 1 is determined from observed wind interpolation. The nighttime flow regime within layer 1 is influenced by buoyancy, terrain, warm cities, geostrophic forcing, and frictional forces. These are all accounted for in the flow model formulation. The air within the cold radiation inversion layer is treated as being of constant density and in hydrostatic balance with the air above in layer 2, which is of lesser density. The cold inversion layer is considered as a 2-D fluid where the u and v wind components are invariant with height. Solution of the wind sub-model equations produces estimates of the wind components as well as the depth of the inversion layer for all grid cells in model layer 1. Vertical velocities at cell interfaces of bounding layers are calculated from mass continuity considerations.

Initial testing with the ROM will use a simplified chemical kinetic mechanism of gas phase photochemistry of the NO_x-HC-O_3 system developed by Demerjian [8]. The present chemical kinetics will be replaced with

the latest available Carbon Bond chemical mechanism [9] before model evaluation exercises begin. The newer chemical mechanism will also include reaction pathways for the naturally emitted organic species that have been included in the source emissions data base for the first ROM application.

Details of the processes described here and others that are included in the ROM system may be found in other documentation [6,7]. The implementation of the system has been accomplished in a modular fashion. The model core, which solves the model's differential equations expressed in primitive mathematical form, and the data interfaces between model processors and model core are the only parts of the system considered as "hard-wired". The formulations of the processors that generate the wind fields, the interfacial surfaces that separate the layers, turbulence parameters, source emissions and other variables are capable of being easily updated or replaced as long as the data interfaces (input and output parameters) remain the same for each process.

Structural Comparison With Other Regional Oxidant Models

The development of regional scale oxidant models is a relatively recent phenomenon. Most existing models have been developed over the past 5 years and generally are still evolving into new versions as theoretical formulations change. Other grid-based models include STEM [10] and RTM [11]. These models and the ROM all simulate the processes included in O_3 formation and transport on scales of 1000 km. The temporal resolution of the models is typically 1 to 3 hour averaged concentrations. Time steps for the solution of the governing equations are 15 minutes for STEM, 30 minutes for ROM, and a variable time step for RTM dependent upon wind speed and horizontal grid spacing. Typical horizontal resolution on the regional scale is 20-80 km. The ROM is based on a curvilinear coordinate system so that the actual cell sizes vary over the domain; RTM and STEM have fixed cell sizes. The vertical extent of the modeling domain is approximately 2 km for the ROM and RTM and 8 km for STEM. Vertical resolution includes 3 1/2 layers for ROM and 2 1/2 layers for RTM, both of which include a parameterized surface layer. STEM has been used with 11 vertical layers that encompass both boundary layer and free tropospheric processes.

Horizontal wind flows in each model layer are determined by objective interpolation techniques from the observations in all the models. The ROM flow model derives multiple realizations of the flow and assigns probabilities to each as being the correct one. All realizations are consistent with the observations and physical laws jointly. Horizontal transport and diffusion are solved by numerical finite difference methods: an explicit biquintic, semi-Lagrangian polynomial scheme in the ROM, the SHASTA flux-correction technique in RTM, and a 1-D finite element method in STEM. K-theory formulations for horizontal diffusion are used in all 3 models and also for vertical diffusion in STEM. The ROM treats vertical diffusion by volume fluxes of material between layers caused by both turbulent fluctuations in the vertical wind and mean vertical air motion induced by large-scale divergence in the horizontal winds. The RTM neglects

vertical turbulent diffusion and models vertical mass exchange only through mean flow transport and entrainment. In-cloud chemical processes are treated by STEM while the ROM models convective cloud material fluxes and sunlight attenuation. No cloud effects are included in RTM.

All 3 models solve for the contribution from chemical reactions to the species rate equations separately from the other processes modeled because the time scales of reaction can be much smaller than those for the advective-diffusive processes. Time steps for the solution of the chemistry are set small enough to approximate a linearized analytic solution for each species not considered to be in steady state. Steady state approximations for some species are used in STEM and RTM. The ROM does not use steady-state approximations. Sub-grid scale chemical effects from a heterogeneous source distribution are parameterized in the ROM's surface layer. RTM does not explicitly include sub-grid scale chemistry effects, but does model the effects from individual large point sources by a Gaussian puff module embedded within the grid model.

Evaluation and Application

In classical studies of short-range dispersion, atmospheric motion is assumed to consist of 2 distinct components: a large-scale, uniform flow and small-scale fluctuations in the flow, or turbulence. The premise that these components are universal characteristics of atmospheric flow supports the common practice in air pollution models of representing the mean flow by a mathematical expression fit to hourly averaged wind observations and parameterizing the turbulence effects by eddy diffusivities whose values are taken from empirical data. Lamb [6] shows how these assumptions are not necessarily a sound basis for representing atmospheric motion in regional dispersion models. He then develops a conceptual and mathematical basis for representing fluid motion that is consistent with classical definitions of transport and turbulence of short-range boundary layer diffusion and also with dispersion over arbitrarily large scales. Implicit in this conceptual framework is the notion that a uniquely correct flow field can not be determined from a discrete set of wind observations on the regional scale. In fact when one attempts to fit a continuous field to such data using some objective analysis technique, one finds that each technique produces a different field. The constraints imposed by the various techniques are simply mathematical procedures that are not necessarily relevant to the physics of the system.

A technique is developed to derive a discrete set or family of possible flow fields that is consistent with both the observations and the physical laws governing the system. Each flow realization, given a fixed emissions source distribution, maps onto a resultant concentration field after model simulation, although it is impossible to predict the exact concentration field that would occur from among the full set of resultant fields. From this predicted set of concentrations and an estimate of its probability distribution, one can specify the frequency with which the actual concentration can be expected to fall within a

given interval of values in a large number of observations. The width of this interval is a measure of the "predictability" of the concentration. Thus, model evaluation becomes equivalent to testing whether observed concentrations fall within the interval specified with the frequency specified, and if not, whether the failure can be attributed to sampling fluctuation. This approach to model evaluation and model utility is a break from the traditional manner of using air quality models in an absolute fashion, although it is a much more realistic approach for the regional scale.

Application to NECRMP/NEROS Data Base

The Northeast Corridor Regional Modeling Project (NECRMP) ambient data base was assimilated from field data collected during EPA measurement programs conducted in 1979 and 1980 in the northeastern U.S. Figure 4 shows the horizontal extent of the ROM domain as applied to this data base. The NECRMP data base consists of measurements of 4 field experiments: the 1979 Northeast Regional Oxidant Study (NEROS I), the 1980 NEROS II, the Persistent Elevated Pollution Episodes Study (PEPE), and the 1980 Urban Field Studies. Together, these studies have provided a variety of air quality and meteorological measurements on regional, urban, and site-specific scales (12).

Upper air meteorological sounding data were available from 10 National Weather Service (NWS) stations located within the model domain and from 14 additional sites surrounding the region and extending into Canada that are required to resolve boundary conditions. The frequency of balloon releases at selected NWS sites was increased during the EPA field measurement programs from the usual 2 per day at 12 hour intervals to 4 per day at 6 hour intervals. In addition, the NECRMP data base consists of upper air data from 12 special supplementary sites and 4 sodar locations aligned from Virginia to Massachusetts. Also, meteorological data from tetroons, small and large tethered balloons and minisondes are available. The hourly surface meteorological data base consists of various meteorological parameters from 160 NWS stations in the U.S. and Canada, 41 special NECRMP sites and 27 State and local monitoring sites.

Aircraft were also used to collect meteorological and air quality data during the NECRMP field studies. The flight patterns during the 1979 field studies were designed to provide Lagrangian measurements of pollutants within specific air parcels transported across the region. The 1980 aircraft flights were designed to characterize urban plumes, examine urban plume interactions, and also to characterize the regional air mass pollutant concentrations. Among the parameters measured by the aircraft were O_3, NO, NO_x, SO_2, b-scat, temperature, relative humidity, and periodic canister samples for hydrocarbon species analysis. Surface air quality data were collected at 81 State and local sites scattered across the modeling region and 79 special NECRMP sites aligned along the East Coast urban corridor.

The EPA, in conjunction with the individual states in the ROM modeling domain, compiled a complete 1979/1980 NECRMP emissions inventory (13)

specifically addressing the ROM requirements. Environment Canada provided emissions information for those portions of Canada included in the domain. Major point sources, or those stationary sources typically emitting greater than 100 tons per year of any pollutant, are classified separately from mobile and small stationary sources. For electric utilities, State-specific seasonal allocation factors are calculated from power generation statistics and hourly factors are derived from hourly power plant fuel use data. Other point source categories rely on plant-specific operating data for temporal resolution of emissions. Annual area source emissions are temporally subdivided based on information gathered from the literature and previous studies. County emissions are apportioned to the modeling grid system based on the known distribution of surrogate indicators such as housing, population, urban land, agricultural land, composite forestland, airport, and park locations.

The individual grid cells composing the ROM grid for the NECRMP application shown in Figure 4 are 15 minutes of longitude wide in the E-W direction and 10 minutes of latitude in the N-S direction, or about 18.5 km square cells. There are 60 cells E-W and 42 cells N-S. The 3 1/2 layer vertical structure was described previously. Several multi-day periods from the data base will be chosen for model evaluation. The criteria for choosing particular scenarios include sufficient rate of data capture and adequate data quality for specifying all required model inputs. The number of such periods will be more limited than those available on a smaller (urban) scale because of the massive field effort required for data collection on the regional scale. Nevertheless, the NECRMP data base will yield a variety of modeling scenarios suitable for model evaluation, with an emphasis on regional scale high ozone episodes. Analysis and preparation of the data base for choosing the modeling periods are now underway.

Summary

Experience with analyzing ambient air quality data for photochemical pollutants from the Northeast U.S. has shown that interurban and regional transport can have a major effect on ozone concentrations over large areas of that section of the country. This phenomenon is of great concern to those who must design and implement strategies for controlling emissions sources, especially when jurisdiction for such designs lies with individual States whose borders are immaterial to pollutant transport.

EPA's Regional Oxidant Model was designed to simulate the physical and chemical processes that are responsible for photochemical smog within the earth's boundary layer on a 1000 km horizontal scale. This tool thereby provides a means for understanding the regional transport phenomenon and aids in planning for effective control strategies to mitigate the ozone pollutant burden. The framework for the model includes 3 prognostic layers in the vertical extending through to the top levels of cumulus cloud convection and a shallow diagnostic surface layer designed to account for the sub-grid scale chemical effects of a heterogeneous emissions distribution. Among the processes accounted for are advective transport, photochemistry, nighttime wind shear and turbulence episodes, cumulus cloud

effects on vertical mass transport and photochemical reaction rates, terrain influences, biogenic and anthropogenic emissions, and removal by deposition. The uncertainties in defining a regional scale flow field from a limited set of observations are quantified by defining a finite set of wind field "realizations" that are all consistent with the observations and with underlying physical principles. Air quality predictions at specific sites resulting from model simulations with this set of wind fields would take the form of expected probability distributions.

The initial data base for regional model application is that collected during the NECRMP field studies of 1979-80 in the Northeast U.S. For this application the model domain has 60 grid cells E-W and 42 cells N-S with a grid spacing of approximately 18.5 km. Several multi-day periods from the data base will be chosen for model evaluation. Analysis and preparation of the NECRMP data base as well as diagnostic testing of the ROM are now underway.

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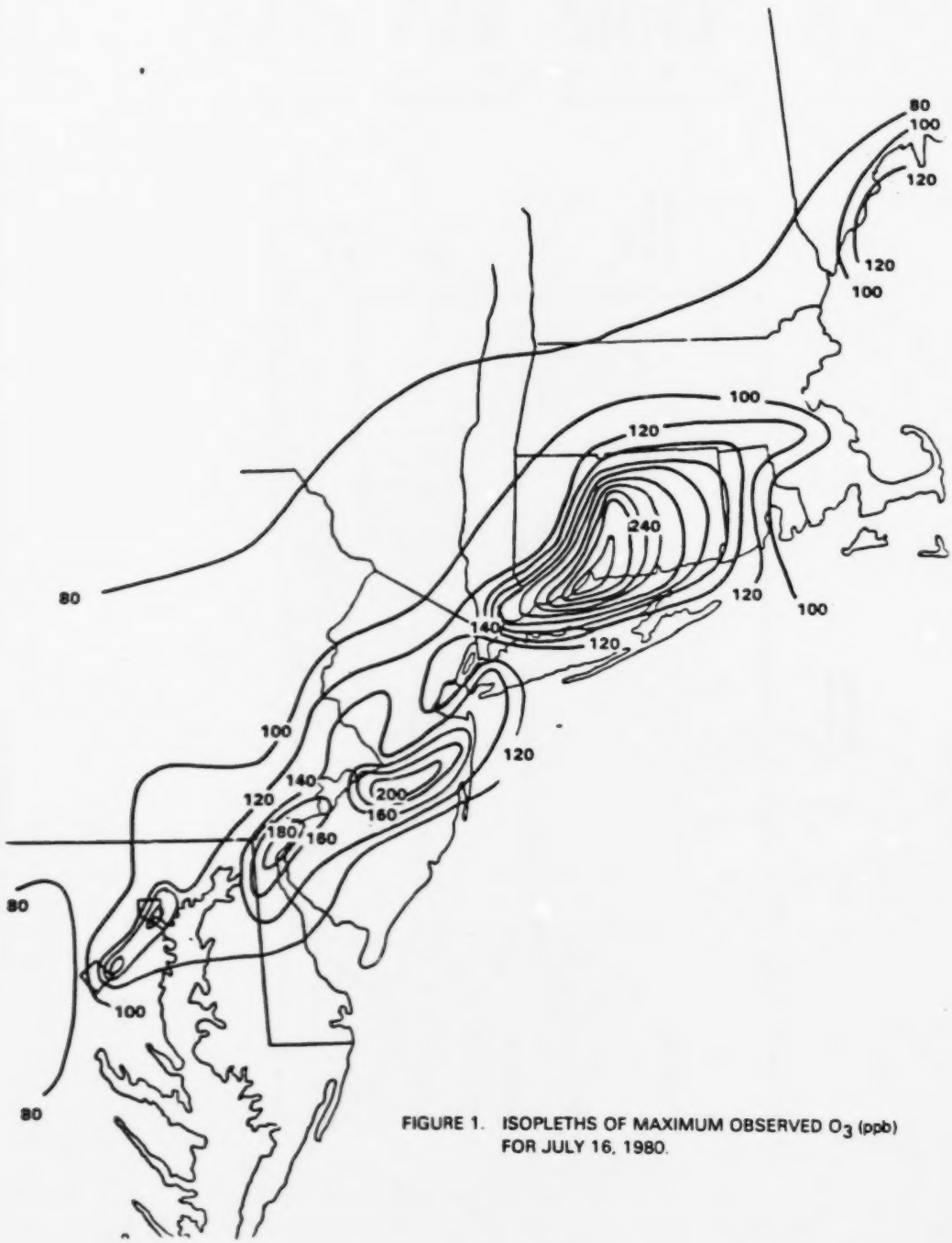

FIGURE 1. ISOPLETHS OF MAXIMUM OBSERVED O_3 (ppb) FOR JULY 16, 1980.

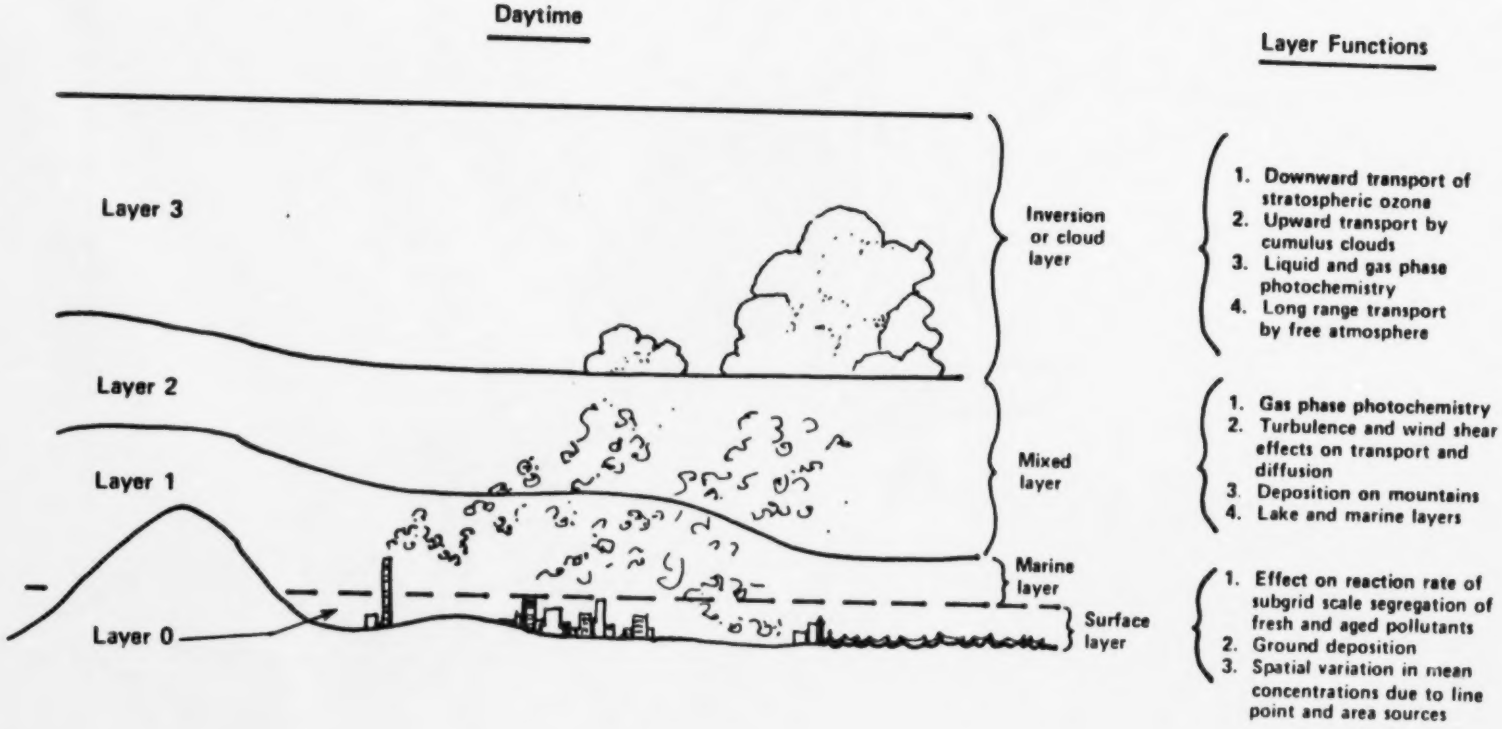
Daytime
Layer Functions
Layer 3
Layer 2
Layer 1
Layer 0
Inversion or cloud layer
Mixed layer
Marine layer
Surface layer
1. Downward transport of stratospheric ozone
2. Upward transport by cumulus clouds
3. Liquid and gas phase photochemistry
4. Long range transport by free atmosphere
1. Gas phase photochemistry
2. Turbulence and wind shear effects on transport and diffusion
3. Deposition on mountains
4. Lake and marine layers
1. Effect on reaction rate of subgrid scale segregation of fresh and aged pollutants
2. Ground deposition
3. Spatial variation in mean concentrations due to line point and area sources

FIGURE 2. SCHEMATIC ILLUSTRATION OF THE ROM VERTICAL LAYER STRUCTURE DURING THE DAYTIME.

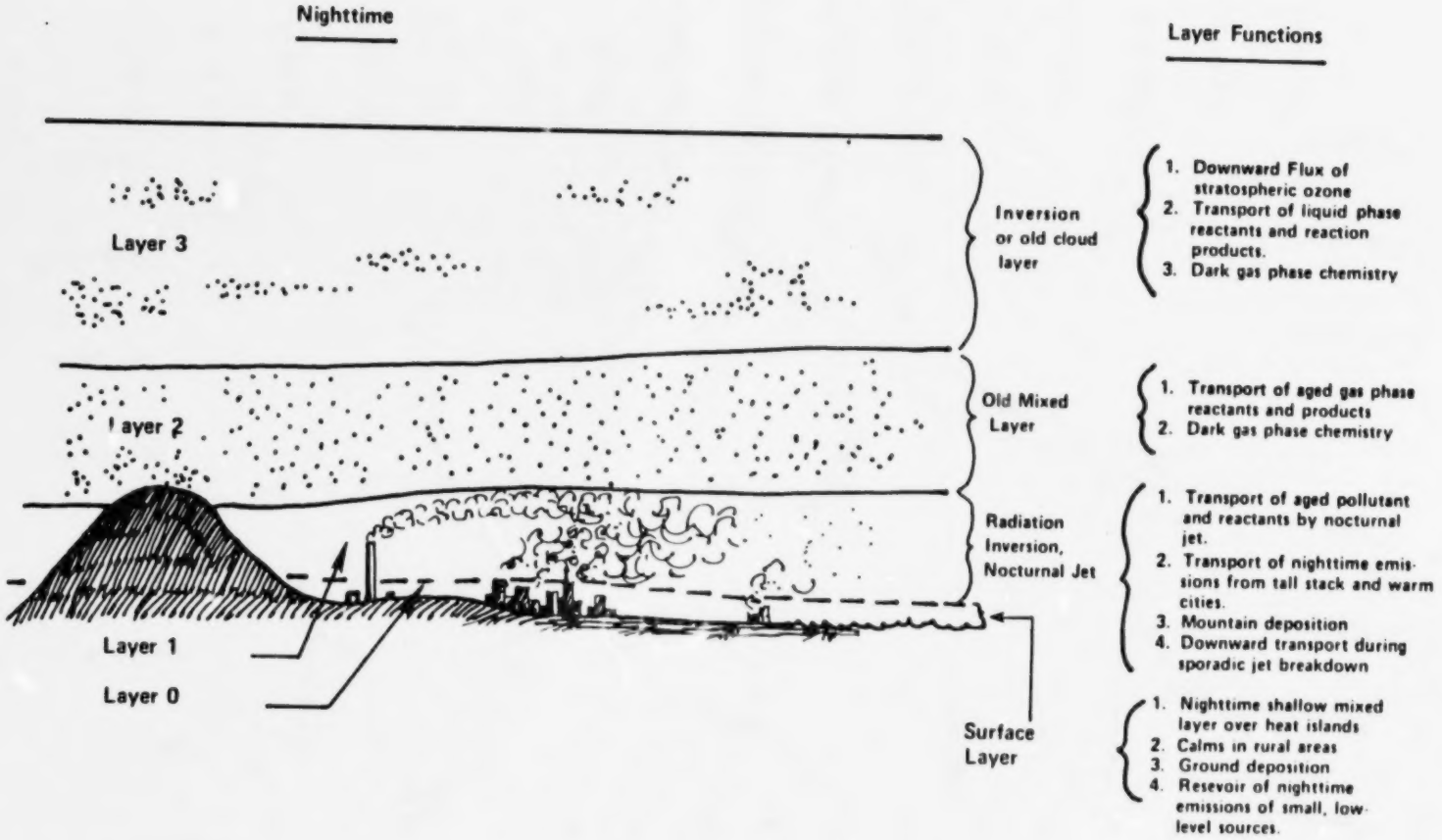
Nighttime
Layer Functions
Layer 3
Inversion or old cloud layer
1. Downward Flux of stratospheric ozone
2. Transport of liquid phase reactants and reaction products.
3. Dark gas phase chemistry
Layer 2
Old Mixed Layer
1. Transport of aged gas phase reactants and products
2. Dark gas phase chemistry
Radiation Inversion, Nocturnal Jet
1. Transport of aged pollutant and reactants by nocturnal jet.
2. Transport of nighttime emissions from tall stack and warm cities.
3. Mountain deposition
4. Downward transport during sporadic jet breakdown
Layer 1
Layer 0
Surface Layer
1. Nighttime shallow mixed layer over heat islands
2. Calms in rural areas
3. Ground deposition
4. Resevoir of nighttime emissions of small, low-level sources.

FIGURE 3. SCHEMATIC ILLUSTRATION OF THE ROM VERTICAL LAYER STRUCTURE DURING THE NIGHTTIME.

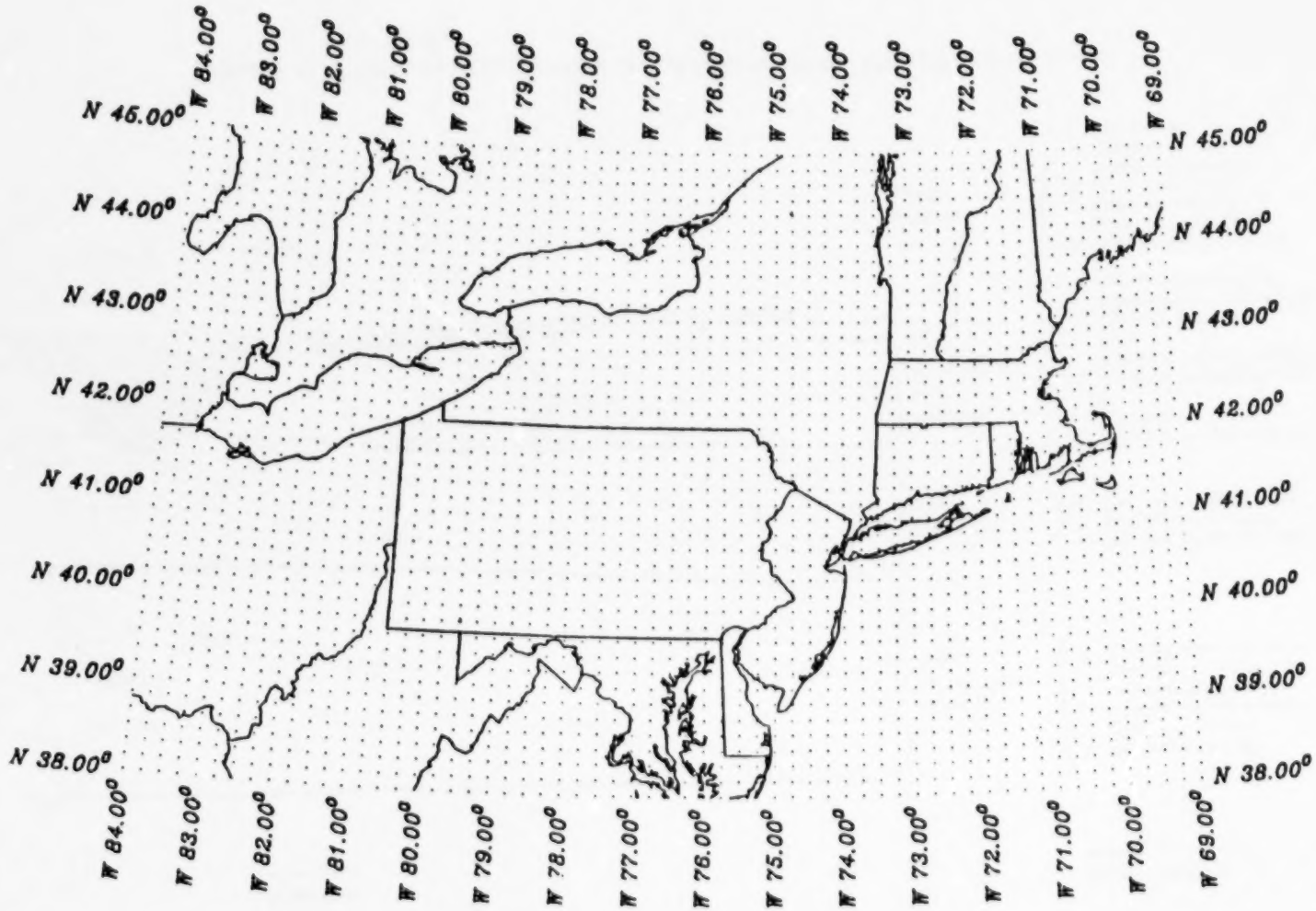

FIGURE 4. MODELING REGION IN THE NEROS STUDY. EACH DOT REPRESENTS A GRID CELL.